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Advancing Fusion by Innovations: Smaller, Quicker, Cheaper

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Abstract. On the path to Fusion power, the construction of ITER is on-going, however there is not much progress in performance improvements of tokamaks in the last 15 years, Fig.1. One possible reason for this stagnation is the lack of innovations in physics and technology that could be implemented with this approach in which progress is expected mainly from the increase in the size of a Fusion device. Such innovations could be easier to test and use in much smaller (and so cheaper and quicker to build) compact Fusion devices. In this paper we propose a new path to Fusion energy based on a compact high field Spherical Tokamak approach.

1. Introduction

We present a new concept of the exploration of Fusion power based on a compact high field Spherical Tokamak (ST). This concept differs from the mainstream path to the Fusion Power via big size devices ITER and DEMO. It allows significant reduction in costs and timescales and allows use of the most advanced technologies and innovations while still fully utilizing all developed Fusion technologies based on 50 years of the development of the Tokamak concept. Such an approach offers the potential to advance the fusion programme and provide a unique integrated system that will help to establish the expertise and techniques for designing and building future fusion power plants, as well as helping to prepare industry for the challenges of building them.

Construction of ITER is progressing, but does not go as fast and is more costly than expected. Certainly there are some subjective reasons for it, but there are also very objective reasons. High mechanical loads, tight tolerances and sizes at the limits of existing technologies have narrowed the industrial basis of ITER manufacturing. Only a small number of the most advanced industries of the world are able to participate in tendering. There is practically no competition and, as a result, very high monopoly prices. The participating companies have no incentive to develop new industrial capabilities and new technologies, because ITER is a single customer. Similar products will be not needed for anybody for next 10-20 years. Even in areas where the government investments have led to development of new products - $NbSn_3$ superconductivity, powerful short wave gyrotrons, MeV neutron beams – absence of customers in immediate future will lead to stagnation. In 20 years' time when the next fusion device will demand similar technologies the people who developed them will be retired and the know-

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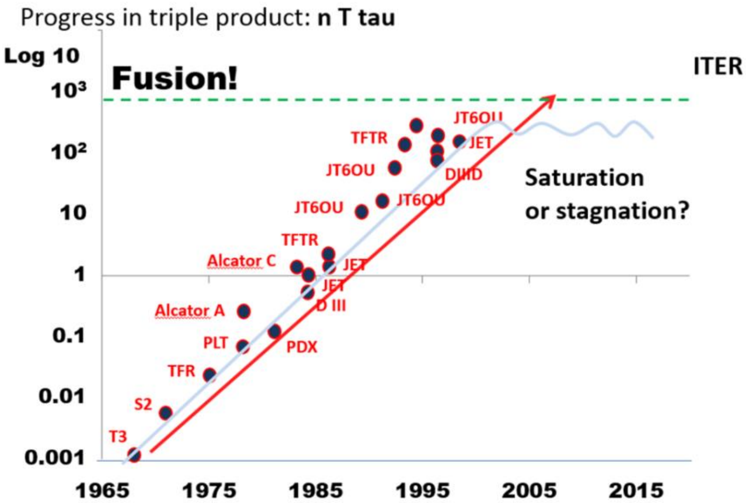

Figure 1. Progress in the triple product (n T tau) in magnetic fusion devices.

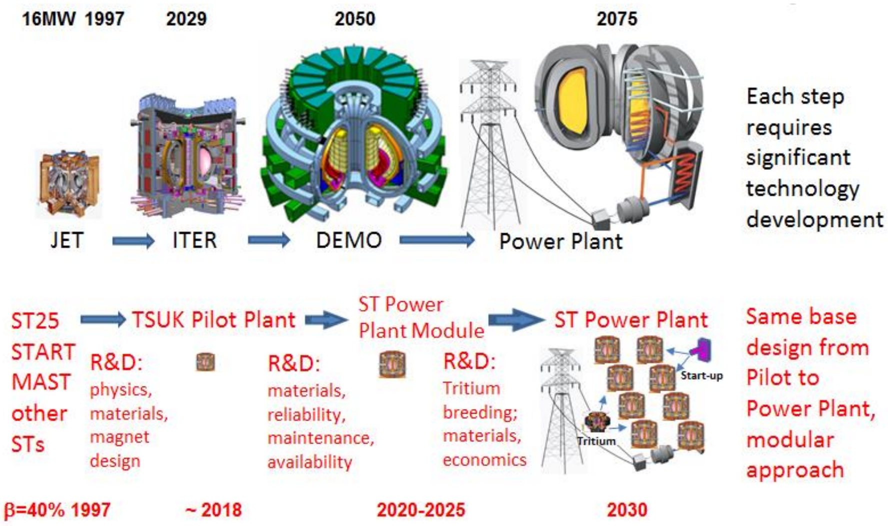

Figure 2. Comparison of roadmaps to Fusion Power: top/bottom – conventional/compact (modular) ST approach.

how will be forgotten. The development of a new technology with very big and expensive prototypes is inevitably slow and not efficient. The new proposed path, based on the compact high field ST approach, has several key features of an executable commercialization strategy [4]: a low-cost pilot plant that can attract commercial cost sharing with minimal financial risk and lead to power plants that are still small on an absolute scale. So many such devices can be constructed opening new sustainable market for the Fusion industry.

There is no question that the final fusion plant will be reasonably big, like all other power plants to day, at the level of 1000 MW(e). If it will be << 500 MW(e), the cost of its conventional part will become prohibitive. We propose another way. One energy conversion plant can serve many small fusion cores combined in one big fusion plant, so we need to build and test only one fusion core. If for example we can build a fusion core with 50 MW(th) fusion power, the total power station will consist of ~50 fusion cores and finally each core must cost < 65M Euros. Of course, the prototype may be several times more expensive and still fully prove solidness and competitiveness of the design. During the construction, the economy of scale will be substituted by economy of mass production. Building many fusion cores even for one station will justify development of new technologies for mass production. Typical learning curve during building of one station will lead to decrease of the mean cost of the first 40 cores below 50% of the first one. Low cost, short time of production and easy change of each core will lead to fast development of the technology and of its industrial base, Fig.2.

The recent advances in the development of high temperature superconductors (HTS) [1], and encouraging recent results on a strong favorable dependence of electron transport on higher toroidal field (TF) in Spherical Tokamaks (ST) [2], open new prospects for a high field ST as a compact fusion reactor. The combination of the high β (ratio of the plasma pressure to magnetic pressure), which has been achieved in STs, and the high TF that can be produced by HTS TF magnets opens a path to lower-volume fusion devices, in accordance with the fusion power scaling proportional to $\beta^2 Bt^4 V$. The proposed ST path to Fusion is described in Section 2. A compact ST can be also considered as an intense and efficient neutron source [3]. Some physics and engineering challenges of such devices will be discussed in Section 3. These include application of HTS in ST magnets, fast particle physics, effect of increase in B_t on micro-stability and plasma confinement, etc. Discussions on advantages of a modular approach are given in Section 4. The demonstration of reliable steady state operations in a compact ST even at the level of a few tens of MW Fusion output as a first step will significantly advance not only the mainstream Fusion for Energy research, but also the commercial exploitation of Fusion Power.

2. ST path to Fusion

We envisage three steps in the development of the ST path to Fusion: the first prototype, the ST Pilot plant and the Power plant module.

The goal of the first prototype is to demonstrate the possibility to produce burning plasma conditions, i.e. main plasma parameters to provide self-heating of the plasma that will be produced by alpha particles born in the DT reaction. As discussed in detail in [1], the proposed way to produce the necessary high toroidal field in a ST can be based on application of high temperature superconductors (HTS) in tokamak magnets. The recent progress in the development of HTS is remarkable and the first application of HTS in tokamak magnets [1] has already confirmed the feasibility of this approach. However the supply chain for production of high quality HTS in the needed quantities is very limited and although significant progress is expected, the timescale of our development path suggests an alternative or combined approach on the first stage of the prototype. This can be achieved in a compact high field ST with non-superconducting toroidal field magnet with HTS used for poloidal field coils only. We will also relax at this stage, requirements on the pulse duration, steady-state operations, full protection of the device from the neutron fluency and on protection of the device first wall and magnets from neutron damage. Short operations with tritium or with very small amounts of it are considered. This prototype will also be used as a research platform for conceptual studies, both in physics and technologies, and can be used as a demonstration of an intense Fusion Neutron Source [3].

Upgrades with high temperature superconducting magnets at the next stage will allow steady-state operations, and improved shielding will protect magnets from neutron damage and heating of magnets in this compact high-field ST Pilot Plant which will demonstrate the possibility of energy production in DT operations. The final stage, probably with an increased size, will provide full demonstration of a commercial Power Plant module.

Commercial opportunities of Fusion today may, or may not be, directly connected with the energy production and indeed the non-power producing applications are more feasible. There are three main opportunities for such commercial applications:

- R&D needed for the Fusion for Energy Research (ITER, DEMO, and support of the mainstream Fusion Research in areas that are not fully explored in presently operating devices);

- Potential application in the Nuclear Industry either as a Fusion core for subcritical systems (hybrid approach) or for waste management
- Commercial and research applications of Fusion neutrons at moderate level, i.e. using Fusion device as an intense Neutron Source.

The 2nd application is the most commercially attractive, but requires substantial development. A compact first step device will not only be a prototype of larger devices for the nuclear application, but readily serve to the 1st and 3rd applications. With the increased size that will allow more shielding and increase in the value of the magnetic field, a compact high field ST will allow demonstration of energy production. The main necessary engineering development for the use of Fusion both in the Nuclear Industry and for the energy production will be in the blanket design, which requires small scale prototypes for development and tests before been commercialized.

This approach is supported by the results of the previous extended studies of the ST path [4, 5] proposing to progress from a small prototype to high-power commercial devices without significant changes in physics and technology.

3. Some physics and engineering challenges of the ST path to Fusion

This new approach is stimulated by successful development of the Spherical Tokamak concept [6] in the last two decades and their obvious ability to produce high Fusion power in moderate size devices. 14 MeV fusion neutrons are produced when a deuterium (D) or deuterium-tritium (D-T) plasma becomes very hot so that the nuclei fuse together, releasing the fast neutrons. It is generally considered that the plasma needs to have high confinement time, high temperature, and high density to optimise this process. As mentioned above, the Fusion power in a reactor can be expressed as

$$P_{fus} \sim \beta_t^2\, B_t^4\, V \qquad (1)$$

where $\beta_t = \langle p \rangle / B_t^2$, $\langle p \rangle$ is average plasmas pressure, B_t is toroidal field and V is the plasma volume.

A tokamak features a combination of strong toroidal field B_t (usually several Tesla) and high toroidal plasma current I_p (several mega-amps) and usually large plasma volume V and significant auxiliary heating, to provide a hot stable plasma so that fusion can occur. The auxiliary heating (usually via tens of megawatts of neutral beam injection of very high energy neutral H or D or T) is necessary to raise the temperature to sufficiently high values before transition to self-heated burning plasma regime occurs. The Lawson criterion requires the "triple product" $n\, T\, \tau_E \sim 3 \times 10^{21}$ kV sec/m^3 for such a regime at optimal conditions for T ~ 14 keV which requires considerably high energy confinement.

	B_t	I_p	$n_e e^{19}$	k	tot
MAST	0.5	0.7	4	2.2	
Compact ST reactor	5	4	50	3	
τ_E gain	1.4	5.1	2.8	1.27	**25**

Table 1. Improvement in confinement in high-field ST following ITER IPB(y,2) scaling.

Increase in toroidal field, plasma current and plasma density will result in significant improvement in the plasma confinement. Table 1 shows this for a device similar to the MAST in size, but with increased parameters. Here ITER IPB(y,2) scaling was used. Assuming typical confinement in MAST of ~0.05 s [2], the predicted confinement will be 1.25 s. If it will be possible to achieve in this device temperatures above 10 keV, the Lawson criterion will be satisfied.

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Although the ITER IPB(y,2) confinement scaling has been confirmed on spherical tokamaks in regimes acceptable for the data to be included in the ITER confinement database, results of recent more detailed studies from MAST and NSTX [2, 7] suggest different scaling which is much more favourable for a compact reactor dependence then with the ITER scaling :

$$\tau_E \sim B_T\text{\^{}}0.9\text{-}1.4 \quad \text{vs} \quad \tau_{E98y,2} \sim B_T\text{\^{}}0.15;$$
$$\tau_E \sim I_p\text{\^{}}0.4 \quad \text{vs} \quad \tau_{E98y,2} \sim Ip\text{\^{}}\ 0.93$$

If this scaling will be applicable for burning ST plasma conditions, parameters of a compact ST to achieve ignition cay be relaxed.

It is well known that stabilization of turbulence by sheared ExB flow is the most possible cause of transport barriers observed in tokamaks; and it has been pointed out that this effect would be very strong in the high shear of the ST leading to improved confinement. More recently, gyrokinetic studies by the NSTX team [8] suggest that the anomalous electron diffusivity decreases more rapidly for hotter, collissionless ST plasmas than for ITER-like plasmas. Gyrokinetic simulations are presently being undertaken [9] on a range of high-field ST (HFST) devices to investigate the possibility that the combination of high field and low-aspect-ratio could stabilize some forms of micro-instability and hence provide the improvement in confinement. They indicate that at low magnetic field the mixing length diffusivity is dominated by electromagnetic tearing modes; these are stabilised at higher B_t, diffusivity then being dominated by electrostatic twisting modes so significant improvement in confinement is expected.

The increase in toroidal field in ST is very favourable for achievement of burning phase. The required increase in the toroidal field can be achieved in STs, where the space for the central column is very limited, even with Cu magnets, however high power dissipation in the Cu magnet drives significant increase in the output Fusion power to achieve the positive economics balance. Fig.3 shows parameters of different superconductors that can replace Cu in the magnet to remove this issue. The left Figure shows dependence of the maximum possible irreversible field at different temperatures for different types of superconductors. The green circle represents the desired regime of operations for a compact high-field ST reactor. This regime can be easily achieved if the 2nd generation of HTS, YBCO tapes, is used. The right Figure shows low degradation of the highest achievable current density in superconductors at different magnetic field. The best low temperature superconductor, Nb_3Sn, shows significant degradation at fields above 25 T, while HTS does not show such degradation. Moreover, if the magnet is designed to position the YBCO tape parallel to the main field, its performance can be significantly enhanced.

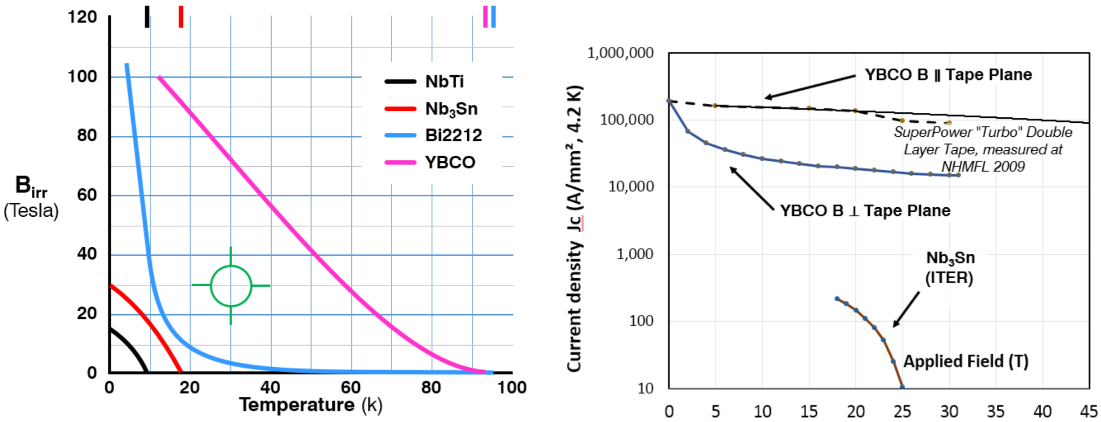

Figure 3. Comparison of different types of superconductors. Left: critical temperature at different magnetic field. The green circle indicates the area of interest for compact high-field ST. Right: critical current dependence on the magnetic field.

So, application of HTS in the ST magnet can allow achievement of high toroidal field needed for ignition, and also compactness of the HTS will provide more space for the necessary neutron shielding in the reactor to reduce requirements for cooling and protect the magnet from neutron damage. However, to achieve high Fusion power, alpha particles providing plasma self-heating must be confined.

In a conventional tokamak fusion reactor the value of the plasma current is determined by two requirements – necessary energy confinement to achieve ignition and necessary alpha particle confinement to heat plasma by fusion reactions. As for STs the energy confinement is a weak function of plasma current and the requirement of alpha-particle confinement may become the decisive one in the determination of the minimum plasma current. The simple estimates based on guiding centre approximation [10] show that to confine 3.7 MeV alpha particles, a plasma current of around 5-6 MA is needed and show a sharp reduction of alpha containment is observed when the plasma current is reduced below this level.

However, recent studies are more encouraging. Taking into account that the Larmor radius of alpha particle (r ~ 0.16/B(T)) is of the same order as the plasma minor radius in compact STs of consideration (a ~ 0.3-0.5 m) and the poloidal field is of the same order as the toroidal field, the most appropriate method to study alpha-particles confinement is a Monte-Carlo code with direct integration of gyro-orbital motion. Such calculations [11] show that in fact rather small plasma currents are sufficient for alpha confinement. Fig.4 presents results of Monte-Carlo modelling of alpha particles in a compact high-field ST. Alpha particle containment fraction and peak wall load dependences on the plasma current are shown at the left plot. The full gyro-orbit model is compared with guiding centre approximation. In the full-orbit case, the reduction of the containment and increase in the wall load are much less steep, because at large currents (even 8 MA) the gyrating particle - in contrast to the guiding centre particle - occupies a cylinder-like volume. This volume, characterized by the Larmor radius, touches the boundary at a distance of a Larmor radius already, thus producing more losses than the guiding centre particles. Thus more guiding centre particles than gyro - particles are lost. Results of full gyro-orbit simulation of alpha power deposition in the compact ST reactor show that the difference in the deposition for 6 MA and 4 MA cases is not significant.

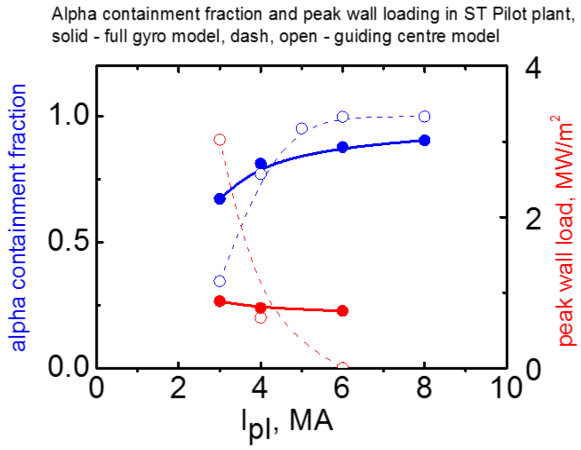

Figure 4. Results of Monte-Carlo modelling of alpha particles in a compact high-field ST. Alpha particle containment fraction and peak wall load dependences on the plasma current. Full gyro-orbit model is compared with guiding centre approximation.

The reduction in the plasma current may result not only in the reduction of the fusion power, but also in a significant increase in the wall load due to lost alpha particles. We have calculated this wall load (e.g. the additional wall load due to lost alphas) for different conditions and found that it is not negligible, but not too dangerous. For a device with the plasma current 4 MA, R/a = 0.8/0.5 m, B_t=5 T, k=3, the total wall load is 2.62 MW and the peak load is 0.8 MW/m^2. The conclusion of these studies is that to calculate losses and deposition profiles in a compact ST, the full-orbit model should be used, which shows less steep dependence on the plasma current. This is very promising, as any reduction in the plasma current will improve the economics of a compact ST reactor.

4. Discussions.

There is no question that the final fusion plant will be reasonably big, like all other power plants today, of a GWe level. However, modular approach does not require multi-GW reactors to be built to test their economics. It is sufficient to build and test only one fusion core module and a compact high field ST reactor is a good candidate for this. Such approach has several obvious advantages:

a. Reliability and availability of the power plant will be improved. If number of fusion cores N >>1, continuity of power can be achieved with a small additional capital cost ~1/N. The power of a modular power plant can be easily adjusted in accordance with grid requirements that change every hour. Such a flexible power station can have higher cost of electricity and still be acceptable by the grid.

b. The engineering costs (>20% for a complex project) will be shared between modules, so will be reduced ~1/N.

c. Internal parts of a fusion reactor become strongly activated during the first hours of operation. The change of the first wall and other repair works must be done by a remote handling equipment which in a single core power plant is idle during operation. Change of the first wall may be done in the most efficient way of changing a total fusion core with a smaller (~ 1/N) increase of capital cost in comparison with a single core power plant and without any loss of availability.

d. Manufacturing of many similar cores will justify development and preparation of special equipment for efficient production, which is usually not justified for production of a single unit (i.e. ITER). Smaller scale of multiple cores will broaden manufacturing basis for their production. Small companies will be able to participate in the tendering process broadening the competition.

For a new technology, big size of components represents not an advantage ("economy of scale"), but a disadvantage. Industries are not ready to prepare new big facilities for manufacturing a single new and risky device or system. As a result number of companies having proper equipment and able to participate in tendering is very small. It leads to a monopoly and high prices.

e. "Learning" of production can be realized during construction of the first module.

With a typical 15% industrial learning curve [12] (it is smaller than usually assumed in current fusion reactor studies when for a reactor N=10 the unit cost is 50% of the reactor N=1) one can expect that the mean cost per core for a reactor with N=40 cores will be below 50% of the cost of the first core. (See Fig 5). It is assumed, that the cost of the second core is equal 80% of the cost of the first on (a typical fission industry figure) and after that the learning rate is 15%, again the most probable industrial number. The prototype core may be at least 2 times more expensive that is needed for the competitiveness and still be acceptable.

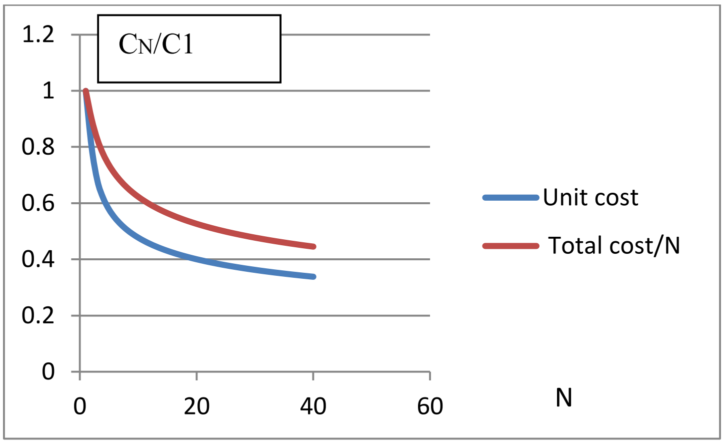

Fig 5. Normalized cost of a core and the mean cost of N cores as function of N.

f. "Economy of scale" in application to fusion devices may be reasonably expected when the "productivity" is proportional to the plasma volume and the "cost" is proportional to surface of the blanket surrounding the plasma to utilise the heat from neutrons for the energy production. Usually, all system codes calculate the cost of a component as the cost of materials and the cost of labour proportional to the cost of materials. The thickness of the fusion blanket and shield is practically constant and so the cost is proportional to the surface of the blanket. So it is beneficial to increase the wall loading up to a reasonable maximum, i.e. to reduce the surface-to-volume ratio, which is a great advantage of the ST geometry.

The cost of the magnet system in a tokamak is clearly depends on β and increase in β decrease the magnet capital cost, but for a fixed machine and a fixed toroidal field higher β means higher wall loading, which beyond some limit may be not desirable. To decrease the cost of the magnet one must use lower magnetic field. The value of magnetic field may be fixed by other considerations, like availability of RF generators for a given frequency, etc. The use of multiple cores permits to decouple β, magnetic field and wall loading by proper selection of the size of a core.

g. The auxiliary heating system of a fusion reactor - a very expensive part of the plant, must heat plasma to ignition point and also support BV ramp-up and increase in β to provide the increase in the bootstrap current fraction. With the modular design, the same system may be a common one for all (or some fraction) of the cores working consequently for each core during the start-up phase, or sharing power between different cores depending on the stage of the pulse.

h. In the modular approach, fusion cores may be pulsed. There is no necessity for steady-state current drive, which significantly increases power recirculation and capital cost of a fusion tokamak reactor. Constant output power may be supported by several pulsed cores with a small additional capital cost (~ 1/N or even << 1/N depending on ratio of pulse duration to dwell duration of a single core). This feature permits optimization of core operations and, for example, operations at high plasma densities for which the existing methods of current drive are very inefficient. For example, an operation regime can be suggested, when the plasma current is almost constant, but the fusion power is modulated by periodical changes of density. The current drive is efficiently performed at periods of low density and low fusion power. Loss of fusion power is compensated by other cores working in this moment of time at the highest plasma density and fusion power.

k. Fuelling/tritium systems for all cores may be combined to use the economy of scale. This common system may be tested separately from the fusion prototype. For the prototype a simplified fuelling/tritium system may be used. Blanket may be represented by just one module. Isotope separation system may be substituted by an external delivery. It will decrease the cost of the prototype even more.

5. Summary

The economy of scale concept can and must be substituted by economy of mass production and optimization, and any innovations could be easier to test and use in much smaller (and so cheaper and quicker to build) compact devices. The main problem of the fusion development is a high risk and a high cost of a prototype (DEMO) needed to justify construction of the power plant. The way to solve the problem is a combination of a big conventional energy conversion plant with multiple fusion cores – relatively small power fusion devices. Only they must be tested by construction of a prototype, significantly reducing the size and the cost of a DEMO. In this paper we propose a new path to the Fusion energy based on a compact high field Spherical Tokamak modular approach, which combines innovations in the Fusion science (ST concept), the Fusion technology (use of HTS magnets) and the Fusion economics (modular approach). We expect that application of these innovations will significantly advance the progress towards the Fusion energy.

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